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FURTHER DEVELOPMENT AND EVALUATION OF M-31 INSULATION FOR RADIANT HEATING ENVIRONMENTS

by VAUGHN F. SEITZINGER
Propulsion and Vehicle Engineering Laboratory

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George C. Marshall Space Flight Center
Huntsville, Alabama

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ABSTRACT

The results of a program for additional development and evaluation of M-31 insulation, a composite material developed specifically to protect the base of the Saturn launch vehicle, are presented. This insulation is comprised of fibrous potassium titanate and asbestos fibers, bonded with colloidal silica. Processing techniques by the manufacturer of potassium titanate resulted in an increase in the bulk density, thermal conductivity, mechanical strength, and drying shrinkage of the insulation.

author

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PROPULSION AND VEHICLE ENGINEERING LABORATORY
RESEARCH AND DEVELOPMENT OPERATIONS

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By Vaughn F. Seitzinger

SUMMARY

The development of an insulation which is composed of fibrous potassium titanate, asbestos fibers, and colloidal silica is described. The composite insulation, designated as M-31, is capable of protecting the base region of the Saturn class launch vehicles from the thermal environments to which they are exposed. Changes made by the manufacturer in the processing techniques for producing fibrous potassium titanate have resulted in changes in the properties of the material. These changes in the properties of the fibrous potassium titanate were investigated to determine their effects on the properties and thermal efficiency of M-31. Also, the effects of gelling the colloidal silica during application of the insulation were studied.

The investigation shows that the changes in the properties of the fibrous potassium titanate increased the thermal conductivity, mechanical strength, bulk density, and drying shrinkage of the M-31; however, these changes did not greatly affect the thermal efficiency of the insulation. By gelling the colloidal silica, the structural integrity of the finished insulation was improved, thereby enhancing its adherence to the substrate to which it is applied. However, this technique of application impaired slightly the material's resistance to radiant heat.

INTRODUCTION

One of the many engineering problems encountered in the development of the Saturn class launch vehicles was devising a method of protecting the base region of the vehicle from the thermal environment to which it was exposed. The heating experienced in the base region of rocket-powered vehicles has been investigated many times; however, the degree of heating experienced by the Saturn class vehicles was considerably more severe than that of previous launch vehicles. The sources of the heat encountered by the base region are radiation from the engine plumes and convection from the recirculating exhaust gases. Nominally, 60 to 80 percent of the total heat is from radiation, with the remainder resulting from convection.

An insulation material for the Saturn base must meet three primary requirements: (1) the material must be capable of providing thermal protection for structural members of the vehicle (maximum allowable temperature for these members was 260°C [500°F]); (2) it must be non-burning since some convective cooling of the base will occur if air that is scooped into the base is not passed through a burning insulation; and (3) it must be easily applied and cured at relatively low temperatures since some areas can be protected only after the vehicle is assembled and oven curing cannot be accomplished.

Based upon the above requirements, efforts were directed toward the development of a low density, highly reflective inorganic insulation which would be resistant to and would insulate against a radiant heat flux of approximately 40 Btu/ft^2-sec. and, at the same time, be resistant to the shock and vibration of launch operations. Since the major component of the total heat load resulted from radiation, attention was focused on selecting a material with a high reflectance in the infrared region. After investigation of many materials, it was concluded that fibrous potassium titanate, available commercially as "Tipersul,"* was the most suitable material for this application.

Successful utilization of fibrous potassium titanate required that it be applied in thick coatings to the heat shield substrates. This necessitated the use of a binder that would provide the insulation with sufficient strength within itself to withstand the environments associated with launch operations. Since organic binders would burn or char under the application of heat, only inorganic binders were considered. An evaluation of several commercial inorganic binders led to the selection of colloidal silica, which proved to be effective. The resulting matrix could be cured at temperatures as low as 82°C (180°F). Although colloidal silica-bonded fibrous potassium titanate fulfilled the insulation requirements, it did not have sufficient strength. Thus, asbestos fibers were incorporated into the composite to provide the required strength. The final composition was designated as M-31 (ref. 1).

Fibrous potassium titanate was a relatively new material when M-31 was developed. In fact, at that time, it was being produced in small batches on a semi-work scale for evaluation only. Efforts on the

* "Tipersul" - Tradename of E. I. du Pont de Nemours, Inc., Wilmington, Delaware.

part of the manufacturer to improve the method of producing the potassium titanate fibers resulted in changing from the batch type process to a continuous process. This production method change resulted in potassium titanate fibers that are longer and more uniform in size. Since the properties of M-31 which were reported previously were determined on material that was prepared from fibrous potassium titanate produced by the batch type process, studies were initiated to determine how the modification in the fiber productive process has affected the properties of M-31. This included redetermining several of the properties of M-31. The results of these studies are reported herein.

"Ludox" HS* colloidal silica was used as the binder for M-31. Articles prepared or impregnated with this binder have hard exteriors and soft interiors. This phenomenon is caused by migration of the silica particles during drying. The soft interior has a low density and is considerably weaker than the exterior. Migration can be prevented by gelling the colloidal silica so that the silica particles are immobilized by attachment to each other and to the substrate. Since it was considered probable that the prevention of migration would improve the structural stability of M-31, studies were undertaken to determine the effects of preventing migration. A procedure for modifying the "Ludox" to prevent silica migration during drying of the insulation also is described herein. The insulation prepared from the modified "Ludox" is designated as M-31X.

Because M-31 had to protect against radiant heat primarily, most of the original work was directed toward developing and evaluating the material for radiant heating environments. As a heat shield material, it will have to protect against convective heating also; therefore, studies were undertaken to evaluate the material for this use. Also, extensive work was undertaken to ascertain some of the limitations of M-31 as an insulation for use in both radiant and convective heating environments.

* "Ludox" HS - Tradename of E. I. du Pont de Nemours, Inc., Wilmington, Delaware

PROCEDURE

Sample Preparation

The materials selection and sample preparation were accomplished according to MSFC-SPEC-197A, "Insulation, Thermal, Unfired Ceramic, M-31 for Radiant Heating." Unless otherwise noted, all determinations reported herein were made on M-31 that was prepared from fibrous potassium titanate produced by Du Pont's continuous process. Property measurements were made on the plain M-31 without mechanical reinforcement such as that used in practical applications.

Method of Gelling "Ludox" HS

The following procedure was used for gelling the "Ludox" colloidal silica for the M-31X to prevent migration of the silica particles: (1) add sulphuric acid to the colloidal silica until a pH of 2.5-3.0 is obtained; (2) add 1.5 grams of urea to 100 grams of acidified colloidal silica; (3) use the modified colloidal silica for wet mixing the materials; and (4) use the same drying cycle as for M-31 except the final cure is accomplished at 95°C (203°F) rather than at 83°C (180°F), which is used for M-31. The wet mix prepared with the modified colloidal silica is stiff and difficult to apply. Therefore, in practical applications, extreme care must be taken during application to insure that the material is worked around and under the mechanical devices that are used for bonding purposes.

RESULTS AND DISCUSSION

Engineering Properties

The properties of M-31 are greatly dependent upon the fibrous potassium titanate ingredient. Consequently, changes in the characteristics of the fibrous potassium titanate have a direct effect upon the properties of M-31. For this reason, the following properties were redetermined on M-31, prepared from "Tipersul" fibrous potassium titanate, manufactured by Du Pont's continuous process: (1) bulk density and water absorption, (2) surface hardness, (3) thermal-shock resistance, (4) thermal conductivity, (5) thermal expansion, (6) reflectance, (7) emissivity, (8) mechanical strength, and (9) drying shrinkage.

Bulk Density and Water Absorption. - The bulk density and water absorption were determined according to ASTM Designation C20-46, "Apparent Porosity, Water Absorption, Apparent Specific Gravity, and Bulk Density of Burned Refractory Brick," on M-31 material approximately 1/4-inch thick. The bulk density ranged from 0.85 to 0.91 grams per cubic centimeter (52.9 - 56.6 pounds per cubic foot). The water absorption was determined to be 69, plus or minus 2 percent. The range in the values of both the bulk density and water absorption of M-31 indicates that there is still some variation in the "Tipersul" raw material.

The migration of silica particles to the outer surface of M-31 during drying causes a density gradient through the material. This gradient was determined by grinding off thin layers (approximately 0.020 inch) of a specimen and calculating the density of each layer removed. The density gradient through M-31 is shown in FIG 1, which also shows that there is only a small density gradient through the M-31X which was prepared by gelling the "Ludox." This indicates that the method used to gel the "Ludox" was effective in preventing migration of the silica particles.

Surface Hardness. - The outer surface of the M-31 was determined to have a Mohs hardness of about 6.

Thermal-Shock Resistance. - The thermal-shock resistance was determined on both the reinforced and unreinforced M-31. The reinforced specimens were prepared by applying a 1/4-inch thickness of the material to sheet steel substrates (0.040" x 4" x 6") overlaid with expanded metal that had been attached by fusion tack welds. The unreinforced specimens were 1/4 inch thick, 4 inches wide, and 6 inches long. Three specimens each of the reinforced and unreinforced M-31 were tested. Each sample was subjected to a radiant heat flux of 24 Btu/ft^2-sec. for three minutes and quenched immediately in water. There was no sign of thermal-shock failure of any specimen tested.

Thermal Conductivity. - The thermal conductivity of the M-31 was determined by the Southern Research Institute, Birmingham, Alabama (ref. 2).

M-31 is an anisotropic material. Two factors contribute to its anisotropy: (1) its hard exterior and soft interior caused by migration of silica particles during drying and (2) a partial orientation of both the asbestos and potassium titanate fibers caused by troweling during application. The thermal conductivity of the M-31 was determined in the directions normal and parallel to its plane of application. Figure 2, which illustrates the results of these determinations, shows that the thermal conductivity of the M-31 in the direction parallel to its plane of application is essentially constant at 1.7 $Btu/ft^2/hr/°F/in.$ from 38 to 816°C (100 to 1500°F). The thermal conductivity in the direction normal to the plane of application increases from 0.85 - 1.3 $Btu/ft^2/hr/°F/in.$ in the 38 to 388°C (100 to 730°F) temperature range.

Thermal Expansion. - The thermal expansion of M-31 was determined by the Metallic Materials Branch of this division. Expansion measurements were made along both the hard and soft faces of the material. Specimens two inches long were used for these determinations. The thermal expansion coefficients along the hard and soft faces of the material were determined to be 5.4×10^{-7} and 24.7×10^{-7} per °C, respectively, in the 22 to 600°C (72 to 1112°F) temperature range.

Reflectance. - A Perkin-Elmer Model 112 double-pass, single-beam spectrophotometer equipped with a special integrating sphere was used to measure the absolute spectral reflectance in the 0.30 - 2.2 micron wavelength range. A Hanovia continuous spectrum hydrogen arc source was used in the 0.30 - 0.34 micron wavelength range; a tungsten lamp was used in the 0.34 - 0.85 micron range; and a Globar source was used in the 0.90 - 2.2 micron range. A standard IP-28 photomultiplier tube was used as the detector in the 0.30 - 0.85 micron range, and a lead sulfide cell was used in the 0.90 - 2.2 micron range.

The absolute spectral reflectance of M-31 is illustrated in FIG 3.

Emittance. - The total normal emittance was determined by the Southern Research Institute, Birmingham, Alabama (ref. 3). The results are illustrated in FIG 4, which shows that the emittance is between 0.53 and 0.64 in the 260 to 983°C (500 to 1800°F) temperature range.

Mechanical Strength. - The mechanical strength was determined by a transverse (flexure) test. Measurements were made on an Instron Model TT-B tensile testing machine. The test specimens were 6 inches long, 1 inch wide, and 1/4 inch thick. They were end-supported on round bars, having 7/16-inch radius, spaced 5 inches apart. The load was applied at the center point perpendicular to the specimens. The crosshead (loading) speed was 0.05 inch per minute. The depth and breadth of the specimens were taken at the break. The transverse strength (modulus of rupture) was calculated by the formula:

$$M = \frac{3Pl}{2bd^2}$$

Where M = Modulus of rupture in pounds per square inch

P = The breaking load in pounds

l = Distance between supports in inches

b = Width of specimens in inches

d = Depth of specimens in inches

The effect of water on the strength of M-31 was determined by soaking the specimens in water for 100 hours before making the strength measurements. The effect of gelling the "Ludox" on the strength also was determined. The effect of heat on the strength of M-31 was determined by first subjecting the test specimens to a radiant heat flux of 24 Btu/ft^2-sec. for 155 seconds before making the strength measurements. A total of 15 specimens was used to make each strength measurement. Table I illustrates the results of these measurements.

TABLE I

MODULUS OF RUPTURE OF M-31 MATERIALS

Conditions	Modulus of Rupture - psi	
	M-31	M-31X
Load applied face side	670 (101)	853 (196)
Load applied back side	1, 172 (124)	886 (81)
Wet, load applied back side	926 (190)	710 (136)
Heated at 24 Btu/ft^2-sec. for 155 seconds, load applied back side	995 (120)	

The modulus of rupture values listed in Table I are average values calculated as arithmetic means. The numbers in parentheses are average deviations from the modulus of rupture values. The large deviations are partially caused by variations in the fibrous potassium titanate; however, much of the deviation is caused by the presence of voids in the M-31 insulations, an inherent characteristic of these materials. Table I shows that M-31 loses approximately 15 percent of its original strength when it is subjected to a radiant heat flux of 24 Btu/ft^2-sec. for 155 seconds. This loss of strength is attributed to the effect of heat on the asbestos fibers. Asbestos fibers become very brittle and lose much of their strength when exposed to elevated temperatures. It is known that chrysotile asbestos fibers lose approximately 27 and 65 percent of their strength when they are heated for three minutes at 317°C (600°F) and 650°C (1200°F), respectively. The outer surface temperature of M-31 after being exposed to a radiant heat flux of 24 Btu/ft^2-sec. for 155 seconds is approximately 760°C (1400°F). Soaking the materials in water for 100 hours reduces their strength approximately 20 percent. This reduction in strength is essentially the same for both the M-31 and M-31X. The effect of gelling the "Ludox" on the strength is illustrated clearly. The results show that the strength of this material is practically the same regardless of the direction of the applied load. This indicates that the material is essentially isotropic and that the method used for gelling the "Ludox" was effective in preventing migration of the silica particles.

Drying Shrinkage. - To control the dried thickness of M-31, it is necessary to know the amount of shrinkage that occurs normal to the plane of application during drying. The percent shrinkage was determined by the formula:

$$\frac{WT - DT}{WT} \times 100 = \text{percent shrinkage}$$

Where

WT = Wet Thickness

DT = Dry Thickness

The drying shrinkage of M-31 was determined to be approximately 26 percent.

Effect of Vibration and Flexure

The adherence characteristics of both M-31 and M-31X were determined. For this study, the materials were applied to relatively thin blanks (0.040" x 6" x 11") so that the specimens could be flexed easily. The blanks were fabricated from AISI 410 stainless steel and were overlaid with 22 gauge AISI 302 stainless steel expanded metal that was attached by fusion tack welds spaced on 3-inch centers. The expanded metal had diamond-shaped openings 3/4 inch across the longest dimension and 1/4 inch across the shortest. The overall height of the expanded metal was approximately 0.090 inch, and it weighed 0.50 pounds per square foot. The expanded metal was attached in such a manner as to leave a minimum gap of 0.032 inch between it and the sheet steel blank. Coatings approximately 0.280 inch thick were applied to the substrates, and the material was carefully worked around and under the expanded metal.

A double amplitude displacement flexure test was used for determining adherence. For this test, the ends of the specimen were mounted to a vibrator in such a manner as to allow the specimen freedom to deflect, the maximum deflection occurring at the center. The specimens were vibrated by applying a "g" load through an eccentric cam with a variable speed transmission and a constant speed electric motor. Initially, each specimen was subjected to a "g" load of 11 "g's" (30 cps and a 1/4-inch displacement) for 30 seconds. Then, the "g" load was increased by increasing the vibration frequency 2-1/2 cps at 30-second intervals until the specimen failed. Failure usually occurred by separation of M-31 and substrate; however, the tack welds failed on some specimens. As the vibration frequency was increased, the specimens started to deflect. At a given vibration frequency, the amount of deflection is dependent upon the rigidity and weight of the sample. The "g" load is a function of both deflection and vibration frequency and was calculated by the formula:

$$g = \frac{\frac{d}{2} \times f^2}{32.2}$$

where

g = acceleration expressed as gravities (32.2 ft/sec^2)

d = total deflection at center of specimen in feet

f = vibration frequency in radians/sec (cps x 2π).

Both wet and dry specimens were tested. They were prepared in the same manner except the wet samples were soaked in water for 170 hours before testing. The results are listed in Table II.

TABLE II

ADHERENCE OF M-31 MATERIALS TO STAINLESS STEEL SUBSTRATES

Materials	Conditions Which Specimens Withstood		Conditions at Failure	
	"g" Load	Deflection (Inches)	"g" Load	Deflection (Inches)
M-31 (Dry)	140	1	167	1-1/8
M-31 (Wet)	81	7/8	109	1
M-31X (Dry)	162 (Limit of equipment)	1	Did not fail	
M-31X (Wet)	70	5/8	113	7/8

The results show that the wet materials have considerably less adherence than the dry materials. They also show that gelling the "Ludox" improves the adherence of the coating to the type of substrate described above.

Effect of Radiant Heating

The evaluation of the insulating capabilities of M-31 and M-31X required that their resistances to radiant heating be determined. The radiant heating test apparatus (FIG 5) which was used for these tests consisted of: (1) a lampholder, (2) a gold-electroplated-on-copper lamp reflector (water cooled), (3) a vibrating device, and (4) the necessary accessory equipment. The lampholder accommodates seventeen 1000-watt, 220-volt, quartz-tube infrared lamps. All specimens were tested at a heat flux of 24 Btu/ft^2-sec., as determined by a cold wall calorimeter, while being vibrated at 11 "g's" of acceleration.

The substrates used for these evaluations consisted of stainless steel blanks (0.040" x 6" x 11") overlaid with stainless steel expanded metal attached by fusion tack welds. A chromel-alumel thermocouple was spark-welded to the back side of each specimen. Coatings of M-31 and M-31X were applied to the stainless steel substrates. The coatings were applied on a weight per unit area basis. Equal weights of M-31 and M-31X resulted in coating thicknesses of 0.290 and 0.260 inch, respectively. The variation in coating thicknesses is directly related to the bulk densities of the materials. The effect of radiant heat on these materials is illustrated in FIG 6.

Effect of Convective Heating

Because the Saturn heat shield must afford protection against the recirculating exhaust gases, it was considered necessary to investigate the effect of convective heating on M-31. Samples were prepared by applying M-31 to mild steel blanks (0.038" x 4" x 6") overlaid with expanded metal attached by spot-welding. A thermocouple attached to the back face of each sample was used to measure temperature rise. An oxygen-acetylene blast burner was used as the heat source. Table III illustrates the effects of convective heating.

TABLE III

EFFECT OF CONVECTIVE HEATING ON M-31

Thickness of M-31 (Inches)	Heat Flux Btu/ft^2-sec.	Temperature Rise (°F) 60 sec.	120 sec.	180 sec.
0.310	10.5	97	251	372
0.540	10.5	62	88	101
0.310	30.0	193	505	690
0.540	45.0	120	378	630

There was no visible change in either sample tested at 10.5 Btu/ft^2-sec. The samples tested at the higher heat fluxes turned yellow after approximately 30 seconds and glowed throughout the test. After the test, the exposed areas turned gray. Minor cracking appeared on the surface of these samples during cooling. These results indicate that M-31 is capable of protecting against the small amount of convective heat that reaches the heat shield area from the recirculation of the exhaust gases from the engines.

Limitations of M-31

To provide design criteria for the use of M-31, it was necessary to establish some of its limitations. A program to ascertain these limitations included the following determinations: (1) effect of multiple exposures to radiant heat, (2) effect of water on its performance, (3) effect of high heat fluxes, and (4) effect of weathering. Radiant heat fluxes up to 80 Btu/ft^2-sec. were required for some of these studies. A graphite resistance heated radiator (ref. 4) was used to achieve heat fluxes greater than 24 Btu/ft^2-sec. Unless otherwise noted, the test specimens used for these evaluations were 1/2-inch coatings of M-31 applied to mild steel plates (0.060" x 7" x 7"), which were overlaid with expanded metal.

To determine the effect of multiple exposures to radiant heat on M-31, duplicate samples were exposed to a heat flux of 40 Btu/ft^2-sec. for 150 seconds. Each specimen was exposed four times. The specimens were vibrated at 30 cycles per second with a double amplitude displacement of 1/4 inch throughout each test. The average back face temperature rise at cut-off was 62°C (111°F), 89°C (160°F), 100°C (180°F), and 97°C

(174°F) after the first, second, third, and fourth test, respectively. After the fourth test, it was noted that approximately one-fourth of the M-31 had separated from the substrate. The separation is attributed to the mechanical vibration and differential thermal expansion between the M-31 and its substrate. The back face temperature rise results indicate that M-31 loses some of its insulating effectiveness on repeated exposures to radiant heating up to and during the third exposure. The insulating properties of the M-31 stabilized during the third exposure and were not degraded further during the fourth exposure. Although the back face temperature rise of the third test was slightly higher than that of the fourth test, the results are within the experimental errors of the test conditions.

The effect of water on the performance of M-31 was determined by soaking the specimens in water before subjecting them to radiant heating. For comparison, two samples were tested at 60 Btu/ft^2-sec. and two at 40 Btu/ft^2-sec. The test procedure consisted of soaking the specimens in water for 24 hours and then exposing them to radiant heating for 155 seconds.

This test cycle was repeated six times on each of the four specimens tested. Because of the entrapped water in the samples, the back face temperature never exceeded 100°C (212°F) for any test. The two samples tested at 60 Btu/ft^2-sec. displayed hairline cooling cracks that opened after each test; however, these cracks were so small that they had no real effect on the performance of the material. The only change in the samples tested at 40 Btu/ft^2-sec. was a slight blue discoloration of the M-31 surface that was noted after the first test. There was no change after the initial exposure.

The maximum radiant heat load that M-31 is capable of insulating against was determined. This was accomplished by increasing the heat load until a level was reached at which the material failed. To eliminate accumulated heating effects, a new set of samples was tested at each heat flux level. The results of these tests are illustrated in Table IV, which shows that M-31 (1/2-inch thick) is an effective insulation in radiant heating environments up to heat fluxes of 70 Btu/ft^2-sec. At a heat flux of 80 Btu/ft^2-sec., the material fails rapidly. These results are indicated by the back face temperature rise after 180 seconds of exposure and by visual examination of specimens during and after testing.

TABLE IV

M-31 IN RADIANT HEATING ENVIRONMENTS

Heat Flux Btu/ft^2-sec.	Exposure Time (Seconds)	Back Face Temp. Rise (°F)	
37	180	125	Slight discoloration of surface
50	180	235	Small amount of surface fusion on hot face
70	180	330	Melting of surface started at 75 seconds and continued throughout test
80	180	750	Fusion started at 60 seconds Large roll of glass formed along bottom half of sample Glass mostly cream-colored and streaked

The effect of weathering on M-31 was determined by exposing samples to local atmospheric conditions. These specimens have been exposed for 18 months without showing any deleterious effects other than an accumulation of atmospheric dust and dirt which has slightly discolored their surfaces.

CONCLUSIONS

The change in the method of processing fibrous potassium titanate, which resulted primarily in an increase in the length of the fibers, affected the properties of M-31 as follows: (1) the bulk density increased from 48 to 55 pounds per cubic foot, (2) the thermal conductivity in the direction normal to the plane of application ranged from 0.85 to 0.92 Btu $/ft^2/hr/{}^\circ F/in.$ for the original M-31 insulation compared to 0.95 to 1.3 $Btu/ft^2/hr/{}^\circ F/in.$ for the present M-31 insulation in the 93 to 388°C (200 to 730°F) temperature range, (3) the transverse strength increased from 475 to 670 pounds per square inch, (4) the drying shrinkage increased from 22 to 26 percent, and (5) the absolute spectral reflectance did not change significantly. Although the change in the fiber length of the fibrous potassium titanate resulted in some changes in the properties of M-31, the insulating capability of the material was not greatly affected. In fact, when M-31 was applied on a weight per unit area basis of approximately 450 grams (dry) per square foot, the back face temperature rise for the M-31 prepared with the longer fibers was only 150°C (270°F) after 145 seconds exposure to a radiant heat flux of 24 Btu/ft^2-sec. Under the same conditions, the back face temperature rise for M-31 prepared from the original fibrous potassium titanate was 133°C (240°F).

Gelling the "Ludox" during preparation of M-31X had the following effects on the finished material: (1) it prevented migration of the silica particles which eliminated the density gradient through the material, (2) it increased the bulk density about 12 percent, (3) it increased the strength of the interior of the material, and this enhanced adherence to the substrate, and (4) it impaired slightly the material's resistance to radiant heat.

M-31, 1/2 inch thick, will withstand up to four exposures to radiant heat of 40 Btu/ft^2-sec. for 150 seconds without its insulating capability being adversely affected. Thick coatings (1/2 inch) of M-31 have withstood single exposures to radiant heating of 70 Btu/ft^2-sec. for 180 seconds with the back face temperature rise never exceeding 165°C (330°F). When the material was exposed to a radiant heat flux of 80 Btu/ft^2-sec. for 180 seconds, the back face temperature rise was 399°C (750°F).

Water weakens M-31; however, it enhances its insulating capabilities. Wet samples have withstood six exposures to radiant heating of 60 Btu/ft^2-sec. for 155 seconds. The entrapped water in the specimens does not allow the back face temperature to rise above 100°C (212°F).

Although the greatest asset of M-31 is its capability to protect against radiant heating, it also affords some protection against convective heating. A 0.310-inch thickness of the material was not damaged when it was exposed to a convective heat flux of 10.5 Btu/ft^2-sec. for 180 seconds, and the back face temperature rise was only 207°C (372°F).

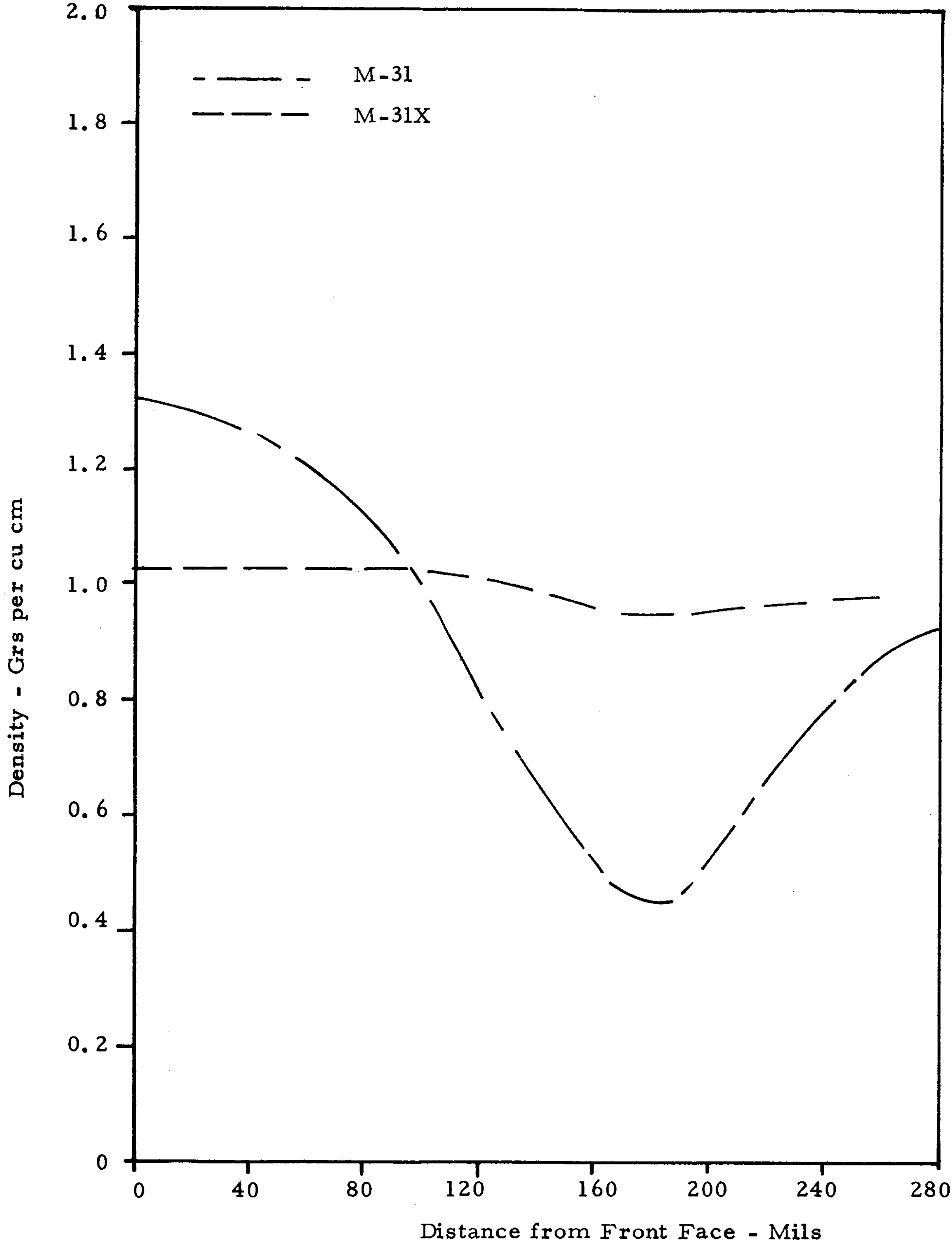

FIGURE 1. DENSITY GRADIENTS THROUGH M-31 MATERIALS

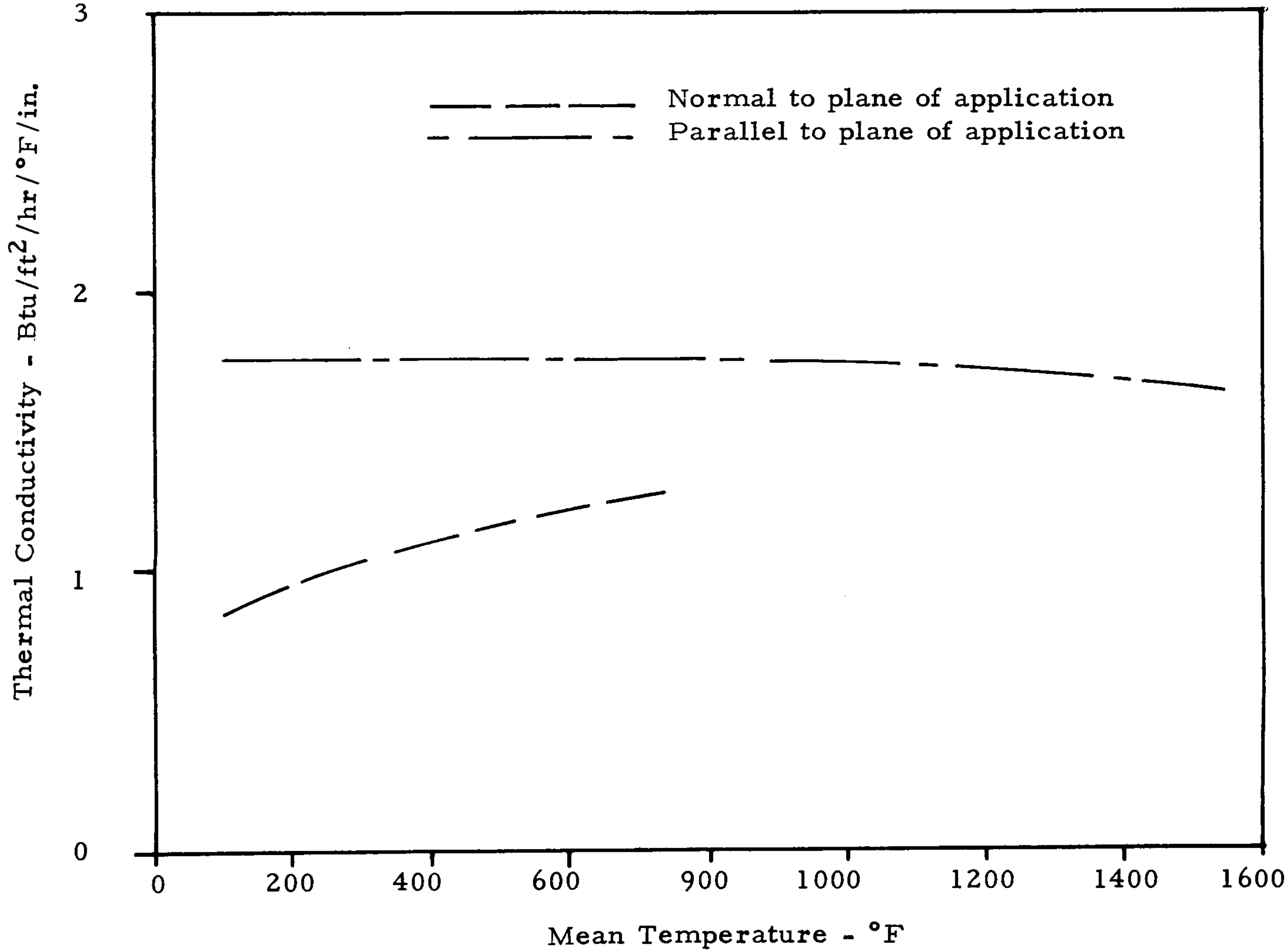

FIGURE 2. THERMAL CONDUCTIVITIES OF M-31

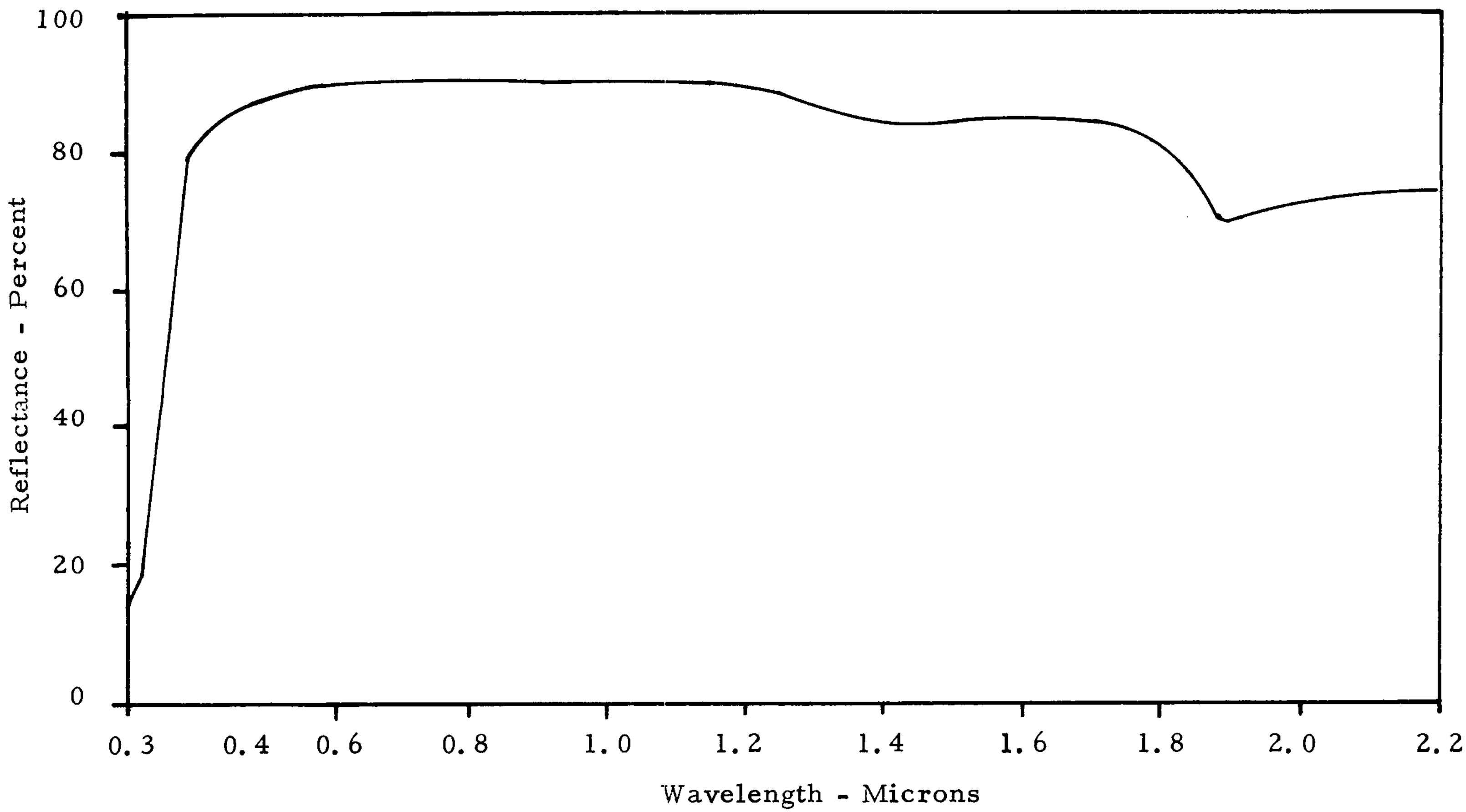

FIGURE 3. ABSOLUTE SPECTRAL REFLECTANCE OF M-31

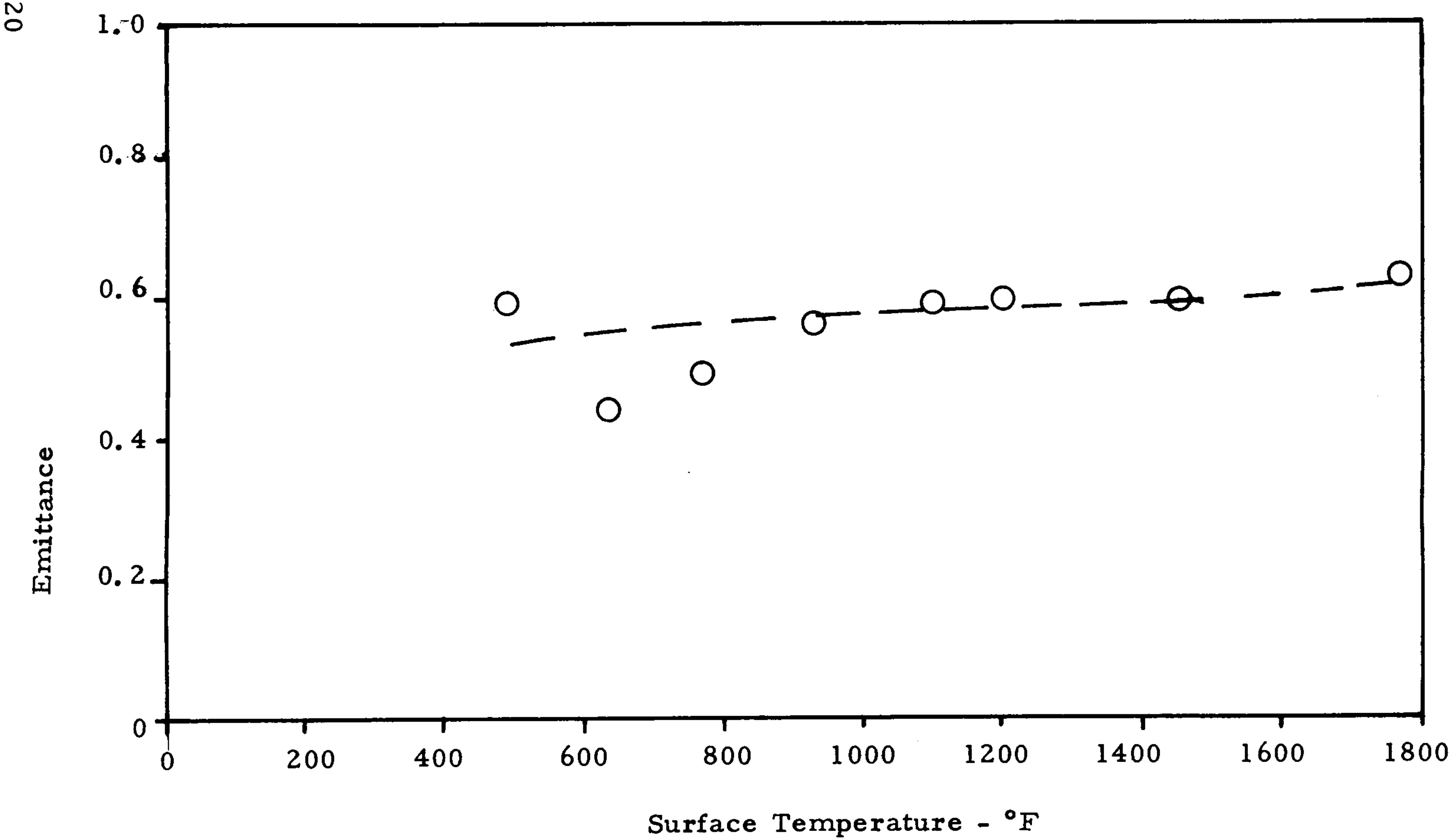

FIGURE 4. TOTAL NORMAL EMITTANCE OF M-31

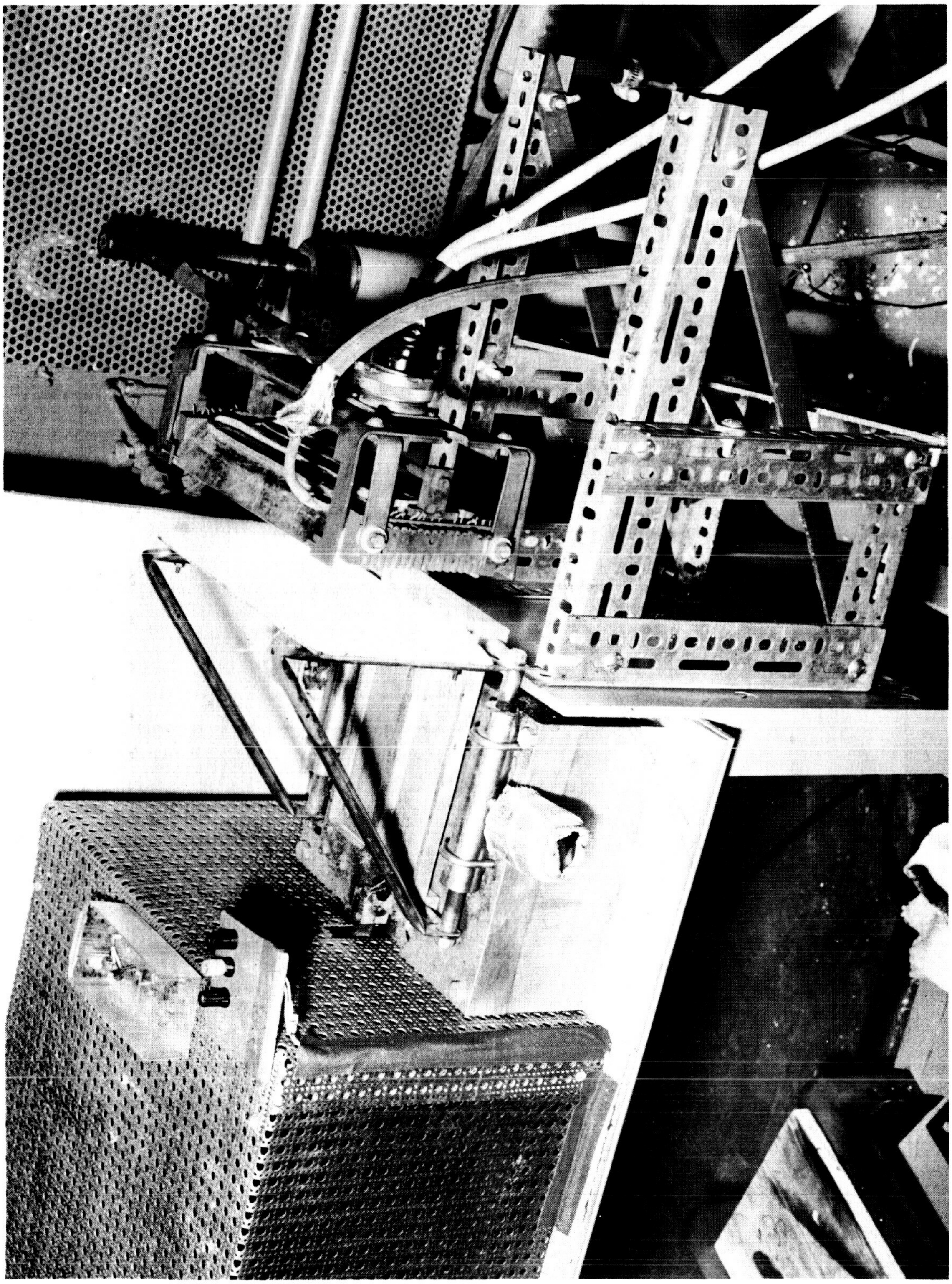

FIGURE 5. RADIANT HEATING APPARATUS WITH M-31 SPECIMEN IN TEST POSITION

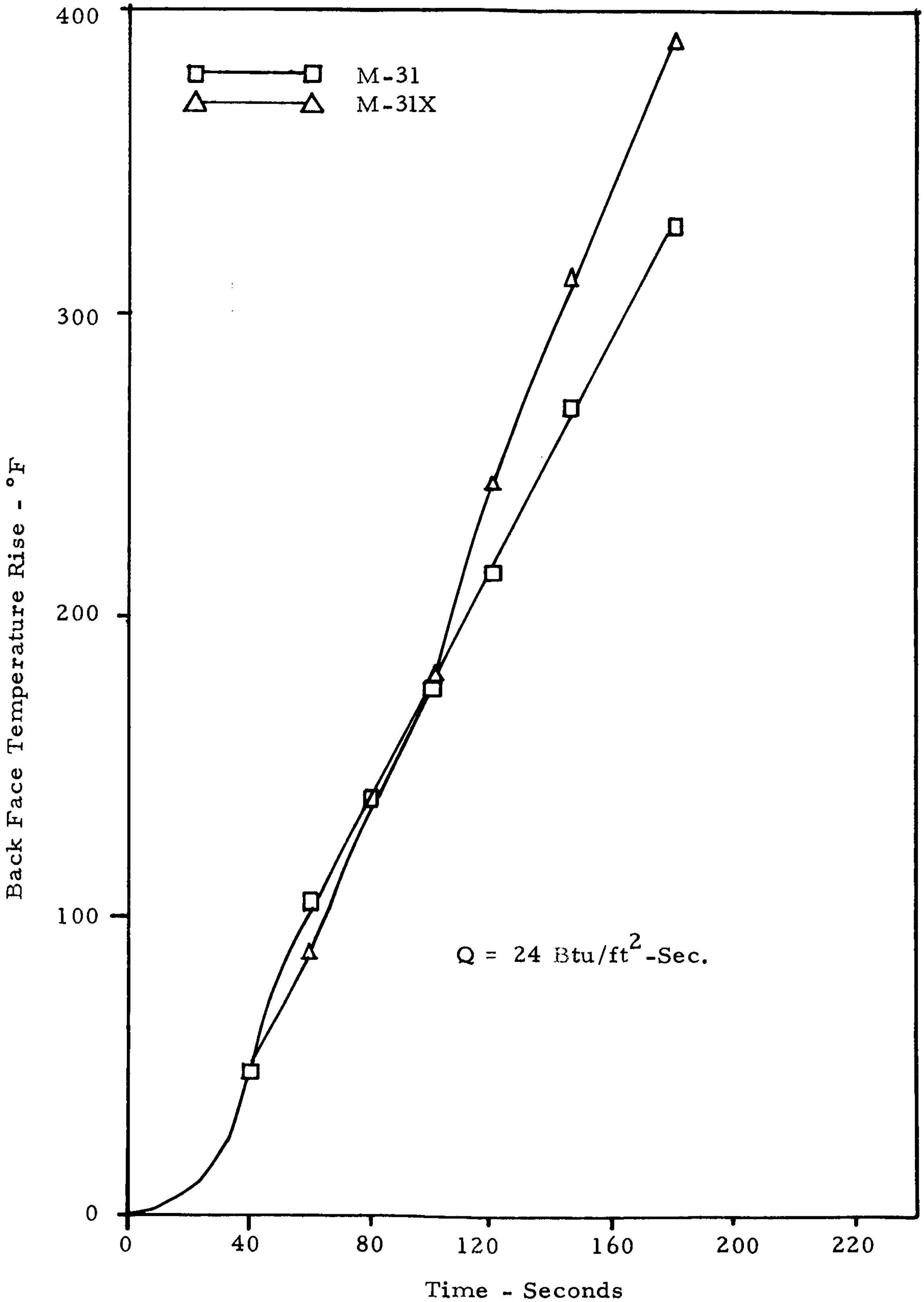

FIGURE 6. EFFECT OF RADIANT HEAT ON M-31 MATERIALS

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FURTHER DEVELOPMENT AND EVALUATION OF M-31 INSULATION FOR RADIANT HEATING ENVIRONMENTS

By Vaughn F. Seitzinger

The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This document has also been reviewed and approved for technical accuracy.

R. E. Shannon

R. E. SHANNON
Chief, Non-Metallic Materials Branch

W. R. Lucas

W. R. LUCAS
Chief, Materials Division

Emil A. Hellebrand

for F. B. CLINE
Acting Director, Propulsion and Vehicle Engineering Laboratory

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